

Finding the Origin of the Pioneer Anomaly

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Abstract

Analysis of radio-metric tracking data from the Pioneer 10/11 spacecraft at distances between 20 - 70 astronomical units (AU) from the Sun has consistently indicated the presence of an anomalous, small, constant Doppler frequency drift. The drift can be interpreted as being due to a constant acceleration of $a_P = (8.74 \pm 1.33) \times 10^{-8} \text{ cm/s}^2$ directed *towards* the Sun. Although it is suspected that there is a systematic origin to the effect, none has been found. As a result, the nature of this anomaly has become of growing interest. Here we present a concept for a deep-space experiment that will reveal the origin of the discovered anomaly and also will characterize its properties to an accuracy of at least two orders of magnitude below the anomaly's size. The proposed mission will not only provide a significant accuracy improvement in the search for small anomalous accelerations, it will also determine if the anomaly is due to some internal systematic or has an external origin. A number of critical requirements and design considerations for the mission are outlined and addressed. If only already existing technologies were used, the mission could be flown as early as 2010.

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1 The Pioneer Missions and the Anomaly

The Pioneer 10/11 missions, launched on 2 March 1972 (Pioneer 10) and 4 Dec. 1973 (Pioneer 11), were the first to explore the outer solar system [1]. After Jupiter and (for Pioneer 11) Saturn encounters, the two spacecraft followed escape hyperbolic orbits near the plane of the ecliptic to opposite sides of the solar system. Pioneer 10 eventually became the first man-made object to leave the solar system.

By 1980, when Pioneer 10 passed a distance of ~ 20 AU from the Sun, the acceleration contribution from solar-radiation pressure on the craft (directed away from the Sun) had decreased to less than 4×10^{-8} cm/s². At that time the navigational data had already indicated the presence of an anomaly in the Doppler data; but at first the anomaly was only considered to be an interesting navigational curiosity and was not seriously analyzed.

This changed in 1994 when, since the anomaly had not disappeared, an inquiry was initiated into its possible origin [2]. The consequence was a long-term collaboration to study and understand the Pioneer data in hand. Useful data were recorded almost up to the end of the official Pioneer 10 mission in 2001, with the last signal from the spacecraft being received on 22 January 2003 [3].

The initial results of the study were reported in 1998 [4] and a detailed analysis appeared in 2002 [5]. For this final analysis the existing Pioneer 10/11 Doppler data from 1987.0 to 1998.5 was used [5]. Realizing the potential significance of the discovery, all *known* sources of a possible systematic origin for the detected anomaly were specifically addressed. However, even after all *known* systematics were accounted for, the conclusion remained that there was an anomalous acceleration signal of $a_P = (8.74 \pm 1.33) \times 10^{-8}$ cm/s² in the direction towards the Sun. This anomaly was a constant with respect to both time and distance, for distances between about 20 to 70 AU from the Sun.

We emphasize *known* because one might naturally expect that there is a systematic origin to the effect, perhaps generated by the spacecraft themselves from excessive heat or propulsion gas leaks. But neither we nor others with spacecraft or navigational expertise have been able to find a convincing explanation for such a mechanism [4]-[6]. This inability to explain the anomalous acceleration of the Pioneer spacecraft with conventional physics has contributed to the growing discussion about its origin.

Attempts to verify the anomaly using other spacecraft proved disappointing. This is because the Voyager, Galileo, Ulysses, and Cassini spacecraft navigation data all have their own individual difficulties for use in an independent test of the anomaly. (See Sections 2.2 and 2.6.) In addition, many of the deep space missions that are currently being planned either will not provide the needed navigational accuracy and trajectory stability of under 10^{-8} cm/c² (i.e., Pluto Express) or else they will have significant on-board systematics (see Sec. 4.2.2) that mask the anomaly (i.e., JIMO – Jupiter Icy Moons Orbiter).

To enable a clean test of the anomaly there is also a requirement to have an escape hyperbolic trajectory. (See Sec. 2.1 for more details.) This makes a number of other missions (i.e., LISA – the Laser Interferometric Space Antenna, STEP – Space Test of Equivalence Principle, LISA Pathfinder, etc.) less able to directly test the anomalous acceleration. Although these missions all have excellent scientific goals and technologies, nevertheless, because of their orbits they will be in a less advantageous position to conduct a precise test of the detected anomaly.

Thus, the origin of this anomaly remains unclear. No unambiguous “smoking gun” on-board systematic has been found [6]. This can be seen by the number of theoretical ideas for new physics that have been proposed to explain the anomaly.¹ By way of illustration, we give two examples. A drag force by enough “dark” mirror-matter could cause the acceleration [7]. The acceleration due to drag from *any kind of* interplanetary medium is

¹For a review and summary up to the start of 2002, see Section XI of [5].

$a_d(r) = -\mathcal{K}_d \rho(r) v_s^2(r) A/m$, where \mathcal{K}_d is the effective reflection/absorption/transmission coefficient of the spacecraft surface being hit, $\rho(r)$ is the density of the interplanetary medium, $v_s(r)$ is the effective relative velocity of the craft to the medium, A is the cross-section of the craft, and m is its mass. A constant density (which would be hard to understand) of 4×10^{-19} g/cm³ would therefore explain the Pioneer anomaly [7].² Another idea is Modified Newtonian Dynamics (MOND) [8], which describes a situation where $F \sim 1/r$ at large distances and which has an acceleration parameter similar to a_P . It has been noted that for a hyperbolic orbit like the Pioneers' there will be an anomalous acceleration similar to ours [8].

With this background, we assert that one can no longer ignore the signal and it is time to experimentally settle the issue with a new deep-space mission that will test for and decide the origin of the anomaly [9, 10]. Here we propose such a new mission, one that would enable an independent and unambiguous test of the Pioneer anomaly and also improve the accuracy of its determination.

When proposing any space mission one needs to address two important issues: the scientific justification for the mission objectives; and the mission configuration and design requirements, including the overall construction, launch, and ground operations cost.

Our arguments above show that there is a strong scientific justification to fly a mission to discover the origin of the Pioneer anomaly. Therefore, in Section 2 we proceed to the mission issues. We review the lessons learned from the Pioneer 10/11 spacecraft, explain the spin-stabilization, on-board power, the “fore/aft”³ symmetric bus and antenna designs, the hyperbolic escape orbit, and the launch concept. In Section 3 we discuss the navigation plan, the data that will be obtained, and the precision with which one can characterize it. Section 4.2 describes the systematics and the error budget for the mission’s fundamental goal – the small acceleration signal. We close with a summary.

Our test is designed to unambiguously determine whether or not the anomaly is due to some unknown physics or else to an on-board systematic. As pointed out in the literature [9, 10], either way the result would be of major significance. If the anomaly is a manifestation of new or unexpected physics, the result would be of truly fundamental importance. However, even if the anomaly turns out to be a manifestation of an unknown systematic mechanism, understanding it will affect the way small forces will be handled in future precision space navigation.

2 Mission Concept

2.1 Applying Lessons from the Pioneers

Our experience, studying both the Pioneer anomaly and also the Pioneer craft itself, has given us much insight into how to design a test of the anomaly. Previously we begun to develop a concept for a mission for such an investigation [9], and we have continued to identify a number of critical design requirements. In this section we will discuss these requirements, their significance, and our approach to addressing them.

To explain what configuration and design will be best for the proposed mission, it first is helpful to summarize what made the Pioneer craft work so well. (See Figure 1.) Among the most important features the Pioneers had were [5]: (i) simple attitude control realized with a spin-stabilized architecture; (ii) on-board nuclear power sources;

²We observe that this argument also holds for normal matter, although there is no evidence for that high a constant density [5].

³DSN radio tracking convention has that when a Pioneer antenna points toward the Earth, this defines the “aft”, “backward”, or “rear” direction on the spacecraft. The equipment compartment placed on the other side of the antenna defines the “fore”, “forward”, or “front” direction on the spacecraft.

2.2 Spacecraft Stabilization

For deep-space navigational purposes the Pioneer spacecraft were much easier to navigate than any other spacecraft, including the Voyagers,⁴ Galileo,⁵ Ulysses,⁶ and Cassini.⁷ This was achieved by utilizing a simple spin-stabilized spacecraft architecture – the two Pioneers were *always* simple spinners.

When in deep space (say at 20 AU or greater), spin-stabilized spacecraft like the Pioneers require only a single maneuver every few months or so to correct for the drift of the antennae pointing direction due to the effect of the craft’s proper motion. Thus, the Pioneers had no continuous- or often-utilized-jetting of attitude control gas. This would have made the navigational accuracy too poor, as happened with the 3-axis-stabilized Voyagers. This is one of the main reasons the Pioneers were so well tracked.

Further, modern 3-axis stabilization relies heavily on the use of precise fuel gauges (to measure fuel usage during maneuvers for input into navigational models), high quality thrusters (for precise attitude control purposes), reaction wheels (to keep preferred spacecraft pointing for a limited time), and often high resolution accelerometers (to track on-board generated non-gravitational disturbances). Although there exist fuel gauges with the desirable precision, thrusters have low repeatability and reaction wheel de-saturation introduces high acceleration noise.⁸ Finally, existing pico-g level accelerometers also have low reliability. This all makes 3-axis stabilization a very costly and undesirable choice for our deep space mission.

Existing spin-stabilized attitude control technology (including in-space propulsion modules, fuel gauges, and even thrusters – because they are seldom used), enables orbit determination precise to better than⁹ $\sim 0.003 \times 10^{-8}$ cm/s² (see Section 4.1), more than two orders of magnitude smaller than the level of the error in the Pioneer anomaly. Therefore, when considering the new mission architecture, we prefer a spin-stabilized spacecraft as opposed to one that is 3-axis stabilized.

2.3 On-board Energy Source

Because this will be a deep-space mission, the distance and time involved rule out solar cells or batteries. An autonomous nuclear source is the only viable option for power. There are currently two choices for such an energy source, a nuclear-electric propulsion module (similar to the one that is being considered for the JIMO mission) and Radioisotope Thermoelectric Generators (RTGs).

⁴The Voyagers are three-axis stabilized. The resulting oft-used gas jets yield a navigation error of $\sim 10^{-6}$ cm/s², which is an order of magnitude larger than the Pioneer anomaly [5].

⁵Galileo was only spin-stabilized during Earth-Jupiter cruise. Although this data set was useful to verify the Deep Space Network hardware, it came from so close in to the Sun that it was too highly correlated with the solar radiation pressure to yield a conclusive result [5].

⁶Ulysses had to have an excessive number of maneuvers due to a failed nutation damper. Although the analysis was indicative, individual errors were as much as an order of magnitude larger than the effect [5].

⁷The Cassini craft used reaction wheels during Jupiter-Saturn cruise, obviating precise navigation modeling [11]. There also was a large effect from the RTGs being mounted on the end of the craft.

⁸This was the case for the state-of-the-art propulsion assemblies used for attitude control of the Cassini mission. That mission has only $\sim 40\%$ truster repeatability and significant reaction wheel noise [11].

⁹Indeed, even the Pioneers had a data precision almost as good as this. The size of the effect could be determined well. It was determining the contributions making up the anomaly (the systematics vs. a “true” signal) that was the problem.

The use of a nuclear-electric propulsion module would definitely solve the power problem by providing virtually unlimited power for the scientific instrument. But it would also make precise navigation and any related navigational science investigation a difficult task. (See Section 2.4.) In any event, nuclear-electric propulsion modules are still being developed and have not yet been flown. Therefore, although they do have a very strong potential for deep space exploration in the future, for now they are not a viable solution. They may become the basic propulsion elements and sources for on-board power for missions that will fly 20 years from now.

On the other hand, RTGs are the present conventional source of energy for any deep space mission. By having the RTGs on extended booms, that are deployed after launch, one obtains the rotational stability of the craft discussed above and also gets a reduction in the heat systematics. (See Section 2.4.) This is why, for this new mission, we choose the use of RTGs with a mounting approach similar to that of the Pioneers.¹⁰

2.4 Heat-Symmetric Spacecraft Design

For a nuclear powered spacecraft, perhaps the major navigation systematic in deep space is thermal emission generated by the spacecraft's power system. This is because, with either space-craft centered RTGs or else a space-craft centered nuclear reactor, there are many to hundreds of kW of heat power generated. This also produces at least hundreds of W of electrical power in the bus. The heat dissipation can produce a non-isotropic force on the craft which can dominate a force of size the Pioneer anomaly, especially if the craft is light. For example, only ~ 63 W of directed power could have explained the anomaly the 241 kg Pioneer craft with half its fuel depleted. Therefore, if the RTGs had been placed "forward" they obviously would have yielded a huge systematic

We will eliminate the heat systematic by making the heat dissipation fore/aft symmetric. In a stroke of serendipitous luck,¹¹ the Pioneer RTGs, with $\sim 2,500$ W of heat, were placed at the end of booms. This meant they had little thermal effect on the craft. Further, the rotation of the Pioneer craft and their RTG fin structure design meant the radiation was extremely symmetrical fore-aft, with very little heat radiated in the direction towards the craft. The same concept will be used for this mission, with perhaps shielding of the RTGs to further prevent anisotropic heat reflection.

The electrical power in the equipment and instrument compartments must also be radiated out so as not to cause an undetected systematic. For the Pioneers the central compartment was surrounded by insulation. There were louvers forward to be open and let out excess heat early in the mission and to be closed and retain heat later on when the electrical power was less. The electrical power degrades faster than the radioactive decay because *any* degradation of the thermoelectric components means the electric power degrades from this *on top of* the degradation of the input heat due to the 87.74 half-life of the ^{238}Pu .¹² For this mission, the louvers will be on the side of the compartment so they radiate in an axially symmetric manner as the spacecraft rotates.

In Figure 2 we show a concept design. Although unconventional, a unique feature of our concept is the dual, identical, fore/aft antenna system. A spacecraft design such as

¹⁰In passing we note that if any new missions like this fly, then the Plutonium itself will likely come from Russia with the safety testing and analysis, fuel purification, and heat source fabrication done in the United States. This could inspire international and intra-agency cooperation on the program, since independently there is revived interest in RTGs and in nuclear-electric propulsion [12].

¹¹Because they were the first deep space craft, the Pioneer engineers were worried about the effects of nuclear radiation on the main bus electronics. Placing the RTGs far away at the end of booms was the solution.

¹²For the Pioneers, the time from launch by when the Pioneer 10 electrical power had been reduced to 50% was about 20 years.[6]

this has never been proposed before. However, this symmetric design allows us further to minimize the heat systematic. Any heat reaching the back of the two antennas, despite insulation placed in, around, and in the support of the bus, will be reflected symmetrically fore/aft.

Our preliminary analysis (see Sec. 4.2.2) suggests that with the existing technologies one can balance the fore/aft geometry of the spacecraft to minimize the possible differential heat rejection systematic to the level $\leq 0.03 \times 10^{-8} \text{ cm/s}^2$. Thus, this fore/aft symmetric design greatly reduces the size of any possible heat systematic.¹³

A final factor in the spacecraft heat transfer mechanism that we want to mention is the optical properties of the spacecraft surfaces. This is a challenging issue to discuss quantitatively. The difficulty lies in the precise folding of the reflective insulation blankets and in the precision painting of all the external surfaces. Of course, for our fore/aft design we will make the processes very symmetric. But it is still hard to predict the exact behavior of all the surfaces on the spacecraft after launch, especially after long exposure to the space environment (i.e., solar radiation, dust, planetary fly-byes, etc.). However, this did not seem to affect the Pioneer results [5, 6], and this mission's use of rotating the antennas (described in the next subsection) will obviate any residual effect.

2.5 More Symmetry: Identical fore/aft antennas

One great advantage of the dual, identical, fore/aft antenna system (shown in Figure 2) is the ability to significantly reduce the effect of the recoil force from the radio-communication beam.¹⁴ If the signal is continuously beamed in both directions, the beam radiation reaction will cancel to at least $\sim 0.01 \times 10^{-8} \text{ cm/s}^2$ (depending on the quality of the design and the components used). This is because the beam force in either direction will be $\sim 1 \times 10^{-8} \text{ cm/s}^2$, and a quality control of 1% on the antennas would yield this limit. Thus, there would be no need to account for this systematic.

Given that the antenna is on the scale of 2–2.5 m (the Pioneers had “9 ft” = 2.74 m antennas) and that there is a similar layout to the Pioneers, *except* for the added second antenna, one would expect this craft to be around 300 kg or less. (At launch the Pioneers *with* hydrozene fuel weighed 259 kg.)

But most importantly, after one has determined a precise signal with one orientation (perhaps after a year or two of data taking) then, aided by Sun and star sensors, the craft can be rotated by 180 degrees so the forward antenna will then be backwards and vice versa.¹⁵ Then, if the anomaly is due to an external effect the measurement will remain the same after rotation whereas the force would be in the opposite direction after rotation if it were due to an on-board systematic. A different (non-zero) result in the two orientations would also unambiguously demonstrate that there was both (a) an externally caused anomaly (one-half the sum of the two measurements) combined with (b) an internal systematic (one-half the difference of the two results).

Therefore, this unique “yo-yo” design will yield an *unambiguous test* of whether the anomaly is due to an internal systematic or to some unknown external origin. It is a major element of the mission concept.

¹³For the Pioneers, contributions to the detected anomaly of order 10^{-8} cm/s^2 came individually from the RTGs and power dissipation [5]. (See Section 4.2.)

¹⁴It was 8 W for the Pioneers, which contributed a bias of $\sim 1.1 \times 10^{-8} \text{ cm/s}^2$ to the detected acceleration [5].

¹⁵A very similar rotation, the “Earth Acquisition Maneuver,” was actually performed on Pioneer 10 soon after launch. For a craft like the Pioneers such a maneuver can be done in about two hours and take about 0.5 kg of fuel.

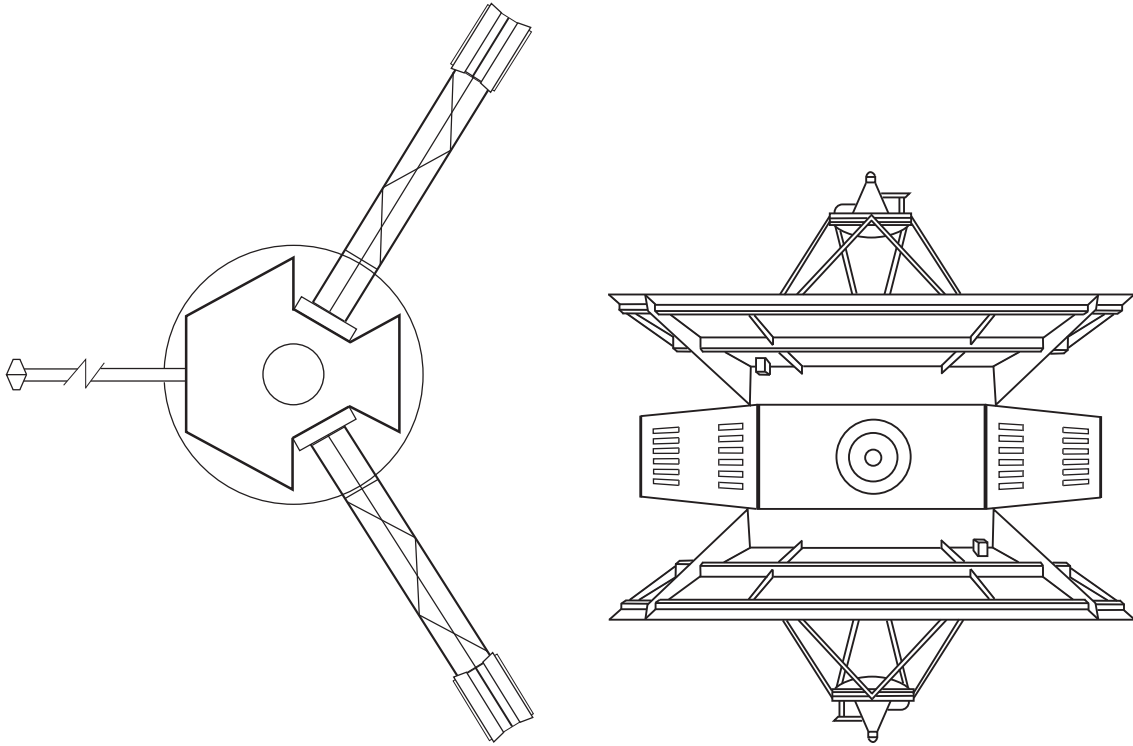


Figure 2: The top (left) and side (right) views (different scales) of our “yo-yo” craft concept. The scale of the circular antenna is on the order of 2 to 2.5 m. The RTGs are deployed on the left. There also is an indication of a third long boom where an instrument package to detect interstellar matter could be placed. Depending on the final mission objectives this instrument package could be replaced by a third RTG. The side view shows the louvers radiating to the side and the antennas, taken and modeled from the Cassini Cassegrain antenna [13].

2.6 Hyperbolic Escape Orbits

The Pioneer anomaly was found on craft following hyperbolic, un-bound, escape trajectories. Contrariwise, solar system data tells us that the anomaly is not seen in the trajectories of large bodies that are bound in low eccentricity orbits. Objects with larger eccentricities, such as long period comets, do show evidence of anomalous behavior, but the significant mass loss masks any signal at the order of the Pioneer anomaly. For the various experimental reasons mentioned in Section 2.2, the indicative data from Ulysses and Galileo in cruise was too noisy to be used to draw any conclusion. There also exist anomalies seen in hyperbolic planetary flybys.¹⁶ This all emphasizes how the transition from bound to escape orbits has never been well characterized [16].

The anomaly was precisely measured between 20 and 70 AU out from the Sun. Although, it might have been present closer in, this has only been imprecisely studied [6]. For this reason and also to reduce the effect of external systematics the experiment should

¹⁶Anomalous energy increases have been observed in Earth flybys; for example in Galileo’s first flyby in 1990 [14, 15] and the NEAR flyby in 1998 [15]. There may also have been a small anomaly in the 1999 Cassini flyby [16].

reach distances greater than 15 AU from the Sun. Obviously, one wants the time needed to reach this region to be short; say, not much more than 6 years. To yield a direct test for any velocity-dependence in the signal, one also wants the craft to have a significantly different velocity than the Pioneers.

All this means that when the craft reaches deep space it should be in a high-velocity, hyperbolic, escape orbit.

2.7 The Launch Vehicle

For a successful mission, the above spacecraft requirements have to be integrated with a launch concept (and also with a total scientific package if there are other experiments).

The launch vehicle is a major consideration for any deep-space mission. To test the Pioneer anomaly cleanly, one wants to reach a distance greater than 20 AU to be able to clearly distinguish any effect from solar radiation pressure and other near-solar systematics. The craft is projected to be of small mass (say, 300 kg or less).¹⁷ Even so, because the desired distance is large (from less than 20 AU to as much as greater than 70 AU) a large solar system escape velocity is desired (say, more than 10 AU/yr). In contrast, the Pioneers are cruising at a velocity of about 2 AU/year and the Voyagers at about 3 AU/year. One needs something faster than that.

The obvious first idea is a very energetic rocket.¹⁸ If a rocket is the source of the large velocity, then a test of Pioneer anomaly might be performed as the radio-science objective of, say, a mission to the outer solar system. We would integrate as many as possible of our design criteria into the constraints of the main mission.

Better yet would be to have our experiment be independent and jettisoned after final powered acceleration so it could fly on alone. This would eliminate any cross-talk systematics from the main mission. A related possibility would be having our mission piggy-back on a large craft having nuclear power as the basis for acceleration, such as the ion engine of the Prometheus program [17]. Here our craft would remain attached to the mother craft until a suitable velocity was reached, say 10 AU/yr. Then our craft would separate to allow our described program of testing for a small force.

It is also interesting, as a speculative alternative, to consider a symbiotic relationship to a solar sail mission. Both NASA [18]-[22] and ESA¹⁹ [23, 24] are developing solar sails. The NASA InterStellar Probe mission concept [18]-[22] would reach the boundaries of interstellar space, the termination shock, the heliopause (> 150 AU), and the bow shock, all expected to be well past 100 AU. The sail would be jettisoned beyond Jupiter. This mission foresees sending a package (of about our size and configuration) at a speed of 14 AU/year. This velocity would be ideal for us and such a mission could also be combined with using a solar sail to detect matter in the ecliptic by measuring the drag force produced [25].

¹⁷The Pioneers weighed 259 kg at launch. Therefore, with a second antenna, 300 kg is a bound which should be improved by using modern materials.

¹⁸The Russian Proton rocket has a very successful record. Using it is an intriguing possibility. Indeed, this again might be a useful option for international collaboration to hold down the cost to NASA or ESA. Further, when the Atlas V, Delta IV, and Ariane V are fully developed, they will provide other potential vehicles. Since launch will be no earlier than 2010, this question can be carefully considered.

¹⁹Through the German Space Agency, ESA is considering a sail for deep-space travel as a development of the earlier Odissee concept [23].

3 Navigation Plan

Even if all systematics were known, no good radio-science data set is possible without good navigation. This implies the use of modern navigational techniques, such as both Doppler and range radio-tracking methods (and perhaps others discussed below [26]).

Doppler measures the velocity of the craft. It only indirectly yields a distance to the craft when one integrates the measured Doppler velocity from known initial conditions. Range itself is a time-of-flight measurement. This is done by phase modulating the signal and timing the return signal which was transponded at the craft. As such, it gives the distance to the spacecraft directly and is a complementary check in the orbit determination. Therefore, range will yield an independent and hence very precise test of the Pioneer anomaly.²⁰

An added precision will be available with the occasional use of Very Long Baseline Interferometry (VLBI) that enables the differenced Doppler (Δ DOR) technique. Δ DOR is similar to ranging, but it also takes in a third signal from a naturally occurring radio source in space, such as a quasar. This additional source helps scientists and engineers gain a more accurate location of the spacecraft.²¹

The mission capabilities might also include the use of multi-frequency communication. This is because multi-frequency communication is useful for correcting dispersive media effects. In particular, it allows the precise calibration of solar and interplanetary plasma systematics. This is why in future missions it would be useful to utilize more than one among the S- (~ 2.4 GHz), X- (~ 7.2 GHz), or Ka- (~ 32.3 GHz) frequency bands. In our discussion below we will concentrate on the use of X-band, because it is presently the standard technology for radio-science, and Ka-band, because it is well en-route to being a standard.

A difficult problem in deep-space navigation is precise 3-dimensional orbit determination. The “line-of-sight” component of a velocity is much more easily determined by Orbit Determination Program (ODP) codes than are the motions in the orthogonal directions. But having both Doppler and range can mitigate this. With the precise, low-systematic data and the analysis of it that we are calling for, a much better than usual determination can be made of the orthogonal dynamics, even to the point of obtaining good three-dimensional acceleration solutions. Additionally, Δ DOR observations will further reduce the uncertainty in the plane-of-the-sky components of the spacecraft proper motion. These navigational capabilities will enable an anomaly test with a sensitivity below 0.003×10^{-8} cm/s² for distances in the range 20 to 90 AU (see Sec. 4.1).

With the radiation pattern of the Pioneer antennae and the lack of precise 3-D navigation, the determination of the exact direction of the anomaly was a difficult task [5]. For standard antennae, and without good 3-D navigation, in deep space the directions (1) towards the Sun, (2) towards the Earth, (3) along the direction of motion of the craft, or (4) along the spin axis, are all observationally synonymous. These directions (see Figure 3) would tend to indicate an origin that is (1) new dynamical physics originating from the Sun, (2) a time signal anomaly, (3) a drag or inertial effect, or (4) an on-board systematic.

²⁰The Pioneers had only Doppler communication capabilities, making impossible any independent verification of the anomaly with a range signal [5].

²¹This “ranging” is not really ranging, but differenced ranging. What is measured is the difference in the distances to the source from two DSN complexes on Earth (for example, Goldstone and Madrid or Goldstone and Canberra). From that an angle in the sky can be determined relative to the stations. The angle for the quasar is subtracted from the angle of the spacecraft, giving the angular separation of the quasar and the spacecraft. That angle is accurate to about five to ten nanoradians. This means that if a spacecraft is near Mars, say 200 million kilometers away, the position of the spacecraft can be determined to within one kilometer. Recently this technique was successfully used in navigating the two Mars missions that carried the rovers Spirit and Opportunity [26].

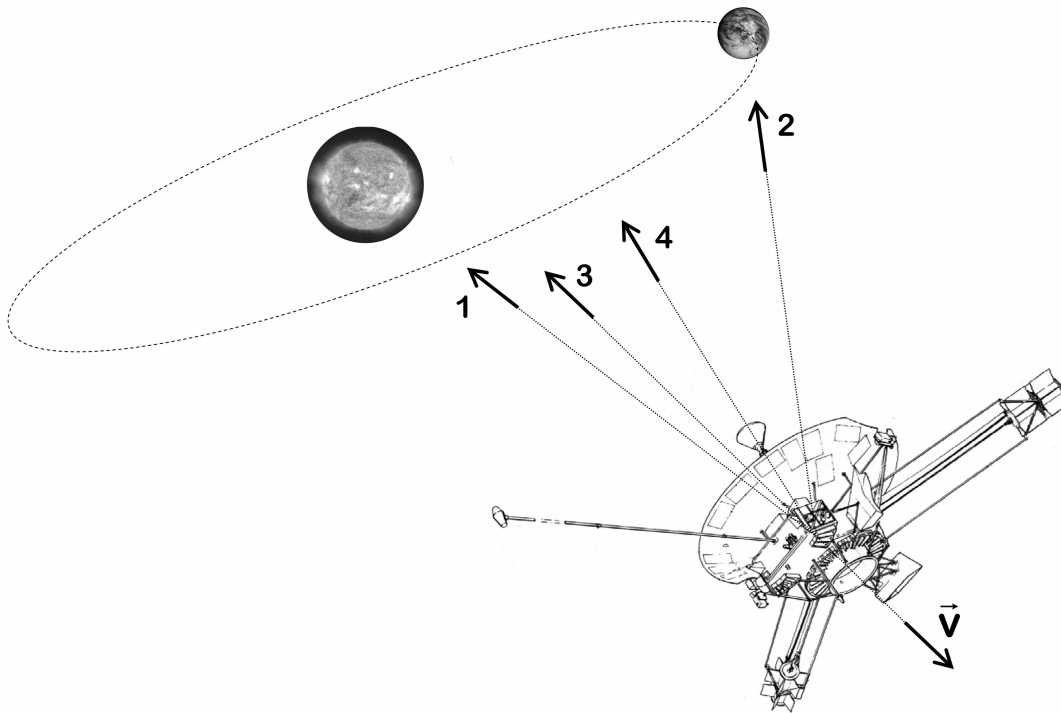


Figure 3: Four possible directions for the anomalous acceleration acting on the Pioneer spacecraft: (1) towards the Sun, (2) towards the Earth, (3) along the direction of motion of the craft, or (4) along the spin axis.

At 20 AU these directions are of order 3 degrees apart (the maximum angle subtended by the Sun and the Earth (even more depending on the hyperbolic escape velocity vector). In Figure 4 we show the angles at which these forces would act for a hyperbolic trajectory in the ecliptic, between 20 and 40 AU. The eccentricity is 5 and the craft travels at approximately a terminal velocity of 5 AU/yr. (a , the minimum distance from the hyperbola to its intersecting asymptotes, is 1.56 AU.) The reference curve (1) at zero degrees is the constant direction towards the Sun. Other angles are in reference to this. Starting to the right in the plane for definiteness, the angle towards the Earth (2) is a cosine curve which is modified by an $1/r$ envelope as the craft moves further out. The angle from the Sun to the trajectory line is shown in (3). Finally, the direction along the spin axis (4) is a series of decreasing step functions. This indicates two maneuvers per year to place the antenna direction between the maximum Earth direction and the null Sun direction, performed as the Earth passes from one side of the Sun to the other.

Looking more closely, it turns out that navigation alone can give evidence to help distinguish among the directions of interest.

A pair of micro-radian quality pointing sensors (for both pointing control and also stability – now standard in the field) will enable one to position the spacecraft with respect to inertial standards of rest to a very high accuracy. The use of 3-D navigation discussed above will result in a precise spacecraft positioning with respect to the solar system barycentric reference frame. As with the Pioneers, the accuracy of the determination will depend on the properties of the antenna radiation pattern. Highly pointed radiation patterns are available for higher communication frequencies. In order to be on the safe side, one can use a standard X-band antenna with a 0.5° angular resolution. Therefore, if the anomaly is directed towards the Sun (1), a combination of the above two methods

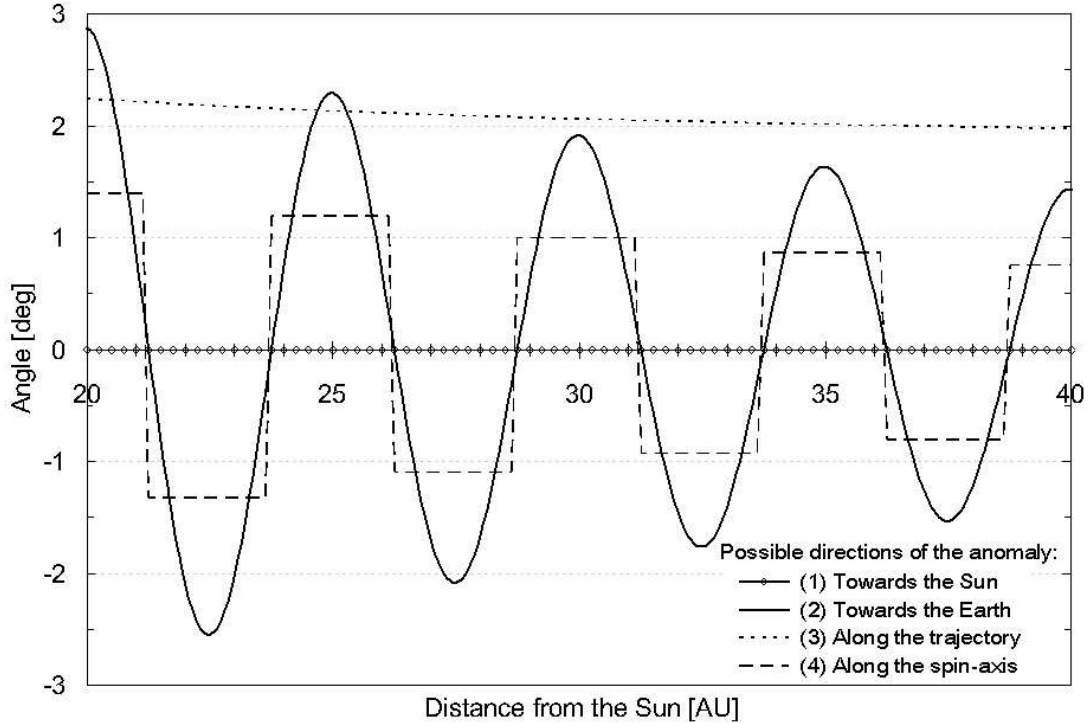


Figure 4: The signatures for four possible directions of the anomalous acceleration acting on the proposed spacecraft. The signatures are distinctively different and are easily detectable with the proposed mission. (See the text.)

will be able to establish such a direction with sufficiently high accuracy.

If the anomaly is directed towards the Earth (2), the current accuracy of the Earth's ephemerides will be a key to determining this fact. Furthermore, in this case one would clearly see a dumped sinusoidal signal that is characteristic to this situation (see above and Figure 4). The use of standard hardware discussed above will enable one to accurately establish this direction with a high signal-to-noise ratio.

Further, an almost-linear angular change approaching the direction towards the Sun (also highly correlated with the hyperbolic trajectory) would indicate a trajectory-related source for the anomaly (3). This situation will be even more pronounced if the spacecraft were to perform a planetary fly-by. In the case of a fly-by, a sudden change in the anomaly's direction will strongly suggest a trajectory-related source for the anomaly.

Finally, a step-function-like behavior of the anomaly, strongly correlated with the maneuver history, would clearly support any anomaly directed along the spin-axis (4). As a result, a combination of the standard navigation methods addressed above in combination of the symmetric spacecraft design (discussed in Sec. 2.4) would enable one to discriminate between these four different directions of the anomaly with a sufficiently high accuracy.

It is clear that these four possible anomaly directions all have entirely different characters. The proposed mission is being designed with this issue in mind. The use of antennas with highly pointed radiation patterns and of star pointing sensors, creates even better conditions for resolving the true direction of the anomaly than does the use of standard navigation techniques alone. On a spacecraft with these additional capabilities, all on-board systematics will become a common mode factor contributing to all the attitude sensors and antennas. The combination of all the attitude measurements will

enable one to clearly separate the effects of the on-board systematics referenced to the direction towards the Sun (1).

This relaxes the requirement on the accuracy of the 3-D spacecraft navigation, allowing it to be as large as $0.01 \times 10^{-8} \text{ cm/s}^2$, as seen from the solar system barycentric reference frame. In Sec. 4.1 we determine that the expected 3-D navigational accuracy will be on the order of $0.003 \times 10^{-8} \text{ cm/s}^2$. At this resolution, the main features of the signatures of Fig. 4 can be distinguished over a year.

This is one of the ways our mission navigation will also provide evidence on the origin of the anomaly, by helping to determine its direction. It will help to decide between the few possible alternative mechanisms and physical causes for the anomaly. This answer will be important in the more general frameworks of the solar system ephemerides as well as spacecraft design and navigation.

In Section 2.5 we described the rotation test that will definitively differentiate between an internal systematic origin for the anomaly and all external origins. For this differentiation the navigational test is a backup to the rotation test. But it will provide information on the spatial direction that the rotation test does not.

4 Expected Accuracy

The current mission plan calls for a nominal mission life time of 7 years (see Table 2). In the initial 3 years the spacecraft will reach a distance of at least 15 AU, where the data will begin to become clear of the solar radiation bias and hence will be of most importance to our investigation. We have the remaining 4 years of the nominal mission life time to conduct the investigation using this cleaner data.

4.1 Data Quality

Both ranging and Doppler data will be used to achieve the required sensitivity level for small accelerations.

As with the Pioneers, the Doppler data could also be time differentiated in batches over days or months in order to obtain independent averages of acceleration at a sample interval equal to the batch interval. With this approach, the standard error, σ_a , for the reduced acceleration data set is proportional to the Allan variance [5], σ_y , for the fractional Doppler frequency ($y = \Delta\nu/\nu$) at 1000 seconds integration time. The proportionality constant is roughly c/τ , where τ is the sample interval for the acceleration data. The relation $\sigma_a = c\sigma_y/\tau$ is commonly used to estimate the expected sensitivity to small accelerations.

Currently, most of the coherent DSN tracking for NASA missions is done by using a standard tracking configuration with X-band ($\sim 8.4 \text{ GHz}$) transmitted and transponded. It is known that by far the dominant error source is spectral broadening of the radio carrier frequency by the interplanetary plasma, with a corresponding increase in Doppler noise. Because of the $1/\nu^2$ dispersive nature of the interplanetary plasma noise, our choice of X-band results in a factor of 10 improvement over S-band ($\sim 2.3 \text{ GHz}$). Ka-band radio-tracking would produce an even better sensitivity to small forces as opposed to the above X-band capability. Ka-band tracking configuration is on its way to being a standard option for NASA missions in the future [27].

For estimation purposes, assume an Allan variance of $\sigma_y = 3.2 \times 10^{-16}$ in 1000 seconds of integration time, which is an appropriate choice for system with a combination of coherent X- and Ka-bands [16]. This results in an expected acceleration sensitivity of $\sigma_a = c\sigma_y/\tau\sqrt{N} \simeq 0.019 \times 10^{-8} \text{ cm/s}^2$ for a one month sample interval, where $N \simeq 2.6 \times 10^3$ is the number of independent single measurements of the clock with duration 1000 seconds

that are performed in one month. This means a year sample would yield accuracy of $\sigma_a \simeq 0.005 \times 10^{-8} \text{ cm/s}^2$.

Furthermore, with 9 months of coherent DSN tracking each year and 4 years of potential data collection, an X-/Ka-band tracking configuration would enable an acceleration sensitivity of $\sigma_a \simeq 0.003 \times 10^{-8} \text{ cm/s}^2$,²² thus increasing our data resolution to any small forces affecting the spacecraft motion.²³

Therefore, our current analysis and mission simulations indicate that the expected 3-D navigational accuracy may be characterized by the following sensitivities: as seen from the solar system barycentric frame: $\sigma_{a_P}^r = 0.003 \times 10^{-8} \text{ cm/s}^2$ in the “line-of-sight” direction. Even with ΔDOR the two remaining orthogonal components will be larger, $\sigma_{a_P}^x = \sigma_{a_P}^y \approx 0.006 \times 10^{-8} \text{ cm/s}^2$. However, since

$$\sigma_{a_P} = \left[\left(\frac{a_P^r}{a_P} \right)^2 (\sigma_{a_P}^r)^2 + \left(\frac{a_P^x}{a_P} \right)^2 (\sigma_{a_P}^x)^2 + \left(\frac{a_P^y}{a_P} \right)^2 (\sigma_{a_P}^y)^2 \right]^{1/2} \quad (1)$$

and we know that $(a_P^x/a_P)^2$ and $(a_P^y/a_P)^2$ are both very small compared to unity, $\sigma_{a_P}^r$ dominates the RMS error.

Therefore, we have $\sigma_{a_P} \approx 0.003 \times 10^{-8} \text{ cm/s}^2$. Although, this is only a preliminary estimate for the potential precision of our acceleration solution, it yields confidence in the experimental concept.

4.2 Systematics

This mission is designed not only to verify the existence of the anomaly but also to clearly determine if the anomaly is due to an external cause or to systematics. In the case of Pioneers, the on-board generated systematics were the largest contributors to the total error budget given in Table II of Ref. [5]. Among the most important constituents, the radio beam reaction force produced the largest bias to our result, $1.10 \times 10^{-8} \text{ cm/s}^2$. Being of opposite sign to the measurement, it resulted in a larger final Pioneer anomaly. The largest bias/uncertainty was from RTG heat reflecting off the spacecraft, $(-0.55 \pm 0.55) \times 10^{-8} \text{ cm/s}^2$. Large uncertainties also come from differential emissivity of the RTGs, radiative cooling, and gas leaks, ± 0.85 , ± 0.48 , and ± 0.56 , respectively, $\times 10^{-8} \text{ cm/s}^2$. The least significant factors of the error budget were those external to the spacecraft and the computational data-handling systematics.

With the exception of the admittedly novel second antenna and the side louvers, much of the craft architecture is specifically taken from the Pioneers. This allows us to once again use the lessons from the Pioneers in analyzing our error budget.

”As with the Pioneers, we have decided to treat all the errors (both experimental and systematic) in a least squares *uncorrelated* manner.”²⁴ The constituents of the error budget are listed separately in three different categories: 1) systematics generated external to the spacecraft and 2) on-board generated systematics. The error itself is conservatively found to be a factor of two orders of magnitude times smaller than the Pioneer anomaly signal.

²²A similar estimate using X-band alone would yield a number around $\sigma_a \simeq 0.01 \times 10^{-8} \text{ cm/s}^2$.

²³A similar estimate can be obtained directly from the results of the Pioneer analysis [5], where a statistical WLS error of 0.01 to $0.02 \times 10^{-8} \text{ cm/s}^2$ was obtained for runs of order 3 years. In fact, one-year runs for the Pioneer S-band data set produced a similar statistical error of $\sim 0.02 \times 10^{-8} \text{ cm/s}^2$. This supports the above estimate obtained by using the higher frequency X-/Ka-bands.

²⁴Combining experimental and systematic errors is a problem that is quite common in experimental physics. The usual solutions are to either treat them as we have or else to list them as two errors in sum for the result. There are un-rigorous arguments for both methods.

Finally, when compared to the biases for the Pioneers, these biases are almost nonexistent (less than the error). This comes directly from the symmetry of our design and mission concept.

The results of our analysis of the systematics of proposed design, given in the remainder of this subsection, are summarized and included in Section 4.3, which serves as a large-constituent “error budget.” This budget is useful both for evaluating the expected accuracy of our solution for a_P and also for guiding possible future efforts with other spacecraft.

4.2.1 External Systematics

As we demonstrated in our previous work [5], the external systematics are all well characterized and mainly very small, depending somewhat on how far out from the Sun the measurements are done. These small systematics are the solar wind, solar corona (especially with the X-/Ka-bands of this mission), electromagnetic Lorentz forces, influence of the Earth’s orientation, mechanical and phase stability of the DSN antennae, phase stability and clocks, and the troposphere and ionosphere [5]. Simply because of the similar size and mass of the craft, these effects which were small for the Pioneers would remain small here. We estimate their combined RMS influence would be $\leq 0.01 \times 10^{-8} \text{ cm/s}^2$.

The expected quality of the data eliminates the need for a more detailed analysis of the computation systematics. Further, the data and the models used to analyze it will introduce an error less than the above. (See Section 4.1.)

The solar radiation pressure is a bias factor that must be accounted for. Standardly the parameterization of the pressure effects for different spacecraft orientations with respect to the Sun is done during early orbit and for the Pioneers was good to better than 5% [28]. Even so, close in to the Sun there can be confusion between this and the computed vs. measured constant RTG systematic, as happened with Cassini.²⁵

The size of the actual solar radiation bias varies, of course, as the inverse of the distance from the Sun. At 20 AU the signal would be around $4 \times 10^{-8} \text{ cm/s}^2$ for the proposed craft. Further, at that distance the craft’s attitude towards the Sun would be less than 3 degrees. This angular variation would provide the only component that would vary from an inverse square fall off and so it becomes vanishingly small. Although there might be some uncertainty (a few kg) in the total mass propellant consumed, at this time very little more would be used. The variation over a year would be less than 1 kg ($\sim 0.3\%$ of the craft’s mass), or a signal varying from $1/r^2$ by a factor of 0.003. But both of these modifications are still on top of the $1/r^2$ variation which at 20 AU decreases by almost 10% in 1 AU. If the craft were going 5 AU/yr, the signal would decrease 36% in a year. Since at this level the signal strength can be determined to about a part in a thousand, we can use our great distance from the Sun to place a bound on the signal’s RMS error of $0.02 \times 10^{-8} \text{ cm/s}^2$.

The only other significant systematic in this category would be from some uncalculated gravity effect, the most likely being from the Kuiper belt. Since the gravitational force is inertial, the same bound can be used as that for the Pioneer craft [5]. There it was shown that this possibility is limited to $0.03 \times 10^{-8} \text{ cm/s}^2$. Although the galactic field is of the size of the Pioneer anomaly, it too can not be the origin of the anomaly. This is because of the fact that Pioneer 11 was traveling roughly in the direction of the solar system’s motion within the galaxy and Pioneer 10 was moving almost in the opposite direction. Further, a galactic tidal force also can not explain the anomaly [5].

²⁵In Earth-Venus cruise, the Cassini orbit determination originally found a significantly different systematic bias from the RTGs mounted on the front than had been predicted by thermal models. This was later determined to have been due the problem of disentangling the RTG systematic from the solar radiation pressure while so close in to the Sun. There the pressure was so much larger and the craft displayed varying aspects to the Sun in the flyby trajectory [29].

As noted in the introduction, the Pioneer anomaly could have been caused by an interplanetary density of 4×10^{-19} g/cm³, that would have to be constant over 50 AU (something hard to understand). Therefore, since this craft will be going at a higher velocity than the Pioneers were and have roughly the cross-sectional area and mass of the Pioneers, the resultant effect would be a factor of $\sim v^2$ higher [25]. Further, 3-dimensional tracking would help show if the acceleration was in the direction of motion of the craft (see Section 3), giving an indication if this were the origin of the anomaly.

4.2.2 On-board Generated Systematics

It is here that our design makes the most significant contribution to error reduction. On-board generated systematic contributed the most significant parts of the total Pioneer error budget of $(+0.90 \pm 1.33) \times 10^{-8}$ cm/s². Because of the rotational cylindrical symmetry of the craft, on-board systematics like the radio-beam reaction force, RTG heat reflection, differential emissivity of the RTGs non-isotropic radiative cooling of the craft, or expelled helium from the RTGs could only contribute fore or aft along the spin-axis.

As we now argue, the additional fore/aft symmetry of the current design should limit the effect of any remaining asymmetry to 0.03×10^{-8} cm/s². This is first because of the small size of any systematics to begin with. However, even more importantly, they can be canceled down to near the navigation data error by the 180° rotation maneuver described in Section 2.5.

For example, what if there is an imperfection in the planned symmetry, such as some of the louvers stick, one of the radio beams does not emit properly, or the two antennas are not equivalent? Well then, after obtaining a “forward” measurement for the anomaly of a_{f1} , when one turns the craft around and measures a new “backwards” a_{b1} , one knows that the anomaly, a_P , and the bias caused by the asymmetry, Δ , are

$$a_P = \frac{1}{2}(a_{f1} + a_{b1}), \quad \Delta = \frac{1}{2}(a_{f1} - a_{b1}). \quad (2)$$

This measurement is limited only by the inaccuracy of the mass determination from fuel usage of about 1/3% craft mass in a year (and the radio frequency measurement error). Normalized to the Pioneer results, multiplying this factor yields an error of 0.03×10^{-8} cm/s², which we take to our fore/aft internal asymmetry error.

The gas leakage error is the hardest to deal with. Small gas leaks that are usually negligible for other missions could in principle cause a problem here.

For the Pioneers there were anomalous spin-rate changes that could be correlated with changes of the exact values of the short term a_P . The correlations between the spin-rate changes and a_P were good to 0.2×10^{-8} cm/s² and better.²⁶

Here we will use modern monitoring to attentively follow the spin-rate changes so as to improve on the observed Pioneer correlations. Further, we will be aided by the current technology development of thrusters (especially the development of μN -thrusters for the LISA mission).²⁷ A final capability is that we will rotate the space craft a first, second, and even more times (say one year runs). The initial value (facing forward) will be a_{f1} . After the first rotation a (backward facing) value, a_{b1} , will be obtained; and similarly thereafter a_{f2} , a_{b2} , etc. Any differences among the a_{fi} ’s and a_{bi} ’s will be a measure of the error introduced by gas leaks. This all leads to an error of 0.04×10^{-8} cm/s².

²⁶But even so, a conservative error of 0.56×10^{-8} cm/s² was quoted [5].

²⁷Consideration can also be given to double-valves that have an escape that is directed along the rotation of the craft.

4.3 Mission Error Budget

The results of the previous discussions can be seen in in Table 1, which gives a summary the significant contributions o the error budget. Adding these errors as RMS one obtains a final error limited to $0.06 \times 10^{-8} \text{ cm/s}^2$. *We emphasize that this is with no bias!* It is a factor of more than a 100 smaller than the Pioneer anomaly! Even with existing technologies, his mission would leave no doubt as to the existence of the anomaly.

This error is how well one will be able to determine the size of the signal, the “accuracy” determined by all the (mainly systematic) errors. This is different than the “precision” of the measurement, which is determined by the statistics. The precision will be smaller, as we discussed in Section 4.1.

Table 1: Summary of *Significant* Error Budget Constituents.

Item	Description of error budget constituents	Uncertainty	10^{-8} cm/s^2
1	Three-dimensional acceleration uncertainty from data		± 0.003
2	Systematics generated external to the spacecraft:		
	a) Solar radiation pressure		± 0.02
	b) Influence of the Kuiper belt’s gravity		± 0.03
3	On-board generated systematics:		
	a) Fore-aft asymmetry (heat, radio)		± 0.03
	b) Gas leakage		± 0.04
Estimate of total error			± 0.06

For context, return to the Pioneer analysis [5]. The “experimental” number obtained is $a_{P(\text{exper})} = (7.84 \pm 0.01) \times 10^{-8} \text{ cm/s}^2$. This statistical error in the data, $0.01 \times 10^{-8} \text{ cm/s}^2$ is very small. That the anomaly is in the data, was independently verified [30]. The precision of the data, there and also here, is not the question.

The Pioneer analysis also found [5] that the systematic *bias and error* are. $(+0.90 \pm 1.33) \times 10^{-8} \text{ cm/s}^2$. This then led to the final number, $a_P = (8.74 \pm 1.33) \times 10^{-8} \text{ cm/s}^2$. Seemingly, this more than 6σ result would appear to be sufficient.

But none-the-less, the main question has become whether or not in some manner or other, systematics could have caused the anomaly anyway. That is, although the calculated bias was $+0.90 \times 10^{-8} \text{ cm/s}^2$, nonetheless, in some not understood way, could the anomaly have been due to systematics?

The mission proposed here, because of the symmetry of the craft, attitude control, navigational capability and the mission design, will have a low *conservative* systematic error of $0.06 \times 10^{-8} \text{ cm/s}^2$ or less, which error cannot be assailed. Therefore, this mission will absolutely settle the above question.

5 A Summary and the Future

In Table 2 we summarize the properties of our mission. This table puts together the various pieces of the program that we have described. With this program the origin of the Pioneer anomaly can be unambiguously determined. In addition, independent of whether a Pioneer Anomaly test will be a stand alone experiment or a probe from a larger mission, we have shown here that such a mission is feasible and also defined its requirements. Any mission concept that may ultimately be chosen will need to be guided by these principles.

Table 2: Mission Summary

Objectives	<ul style="list-style-type: none"> • To search for any <i>unmodeled</i> small acceleration affecting the spacecraft motion at the level of $\sim 0.1 \times 10^{-8} \text{ cm/s}^2$ or less. • Determine the physical origin of any anomaly, if found.
Features	<ul style="list-style-type: none"> • A standard spacecraft bus that allows thermal louvers to be on the sides to provide symmetric fore/aft thermal rejection. • Fore/aft symmetric design with twin antennae (“yo-yo” concept).
Orbit	<ul style="list-style-type: none"> • Solar system escape trajectory – possibly in the plane of ecliptic, co-moving with the solar system’s direction within the galaxy. • Spacecraft moving with a velocity of 5 AU or more per year, reaching 15 AU in 3 years time or less.
Launcher	<ul style="list-style-type: none"> • Delta IV 2425 or any heavy vehicle, i.e., Proton, Ariane V.
Spacecraft	<ul style="list-style-type: none"> • Power at launch: $\sim 200\text{W}$ provided by RTGs located on booms at a distance of $\sim 3 \text{ m}$ from the rotational axis of the spacecraft. • Redundancy: single-string. • Mass: s/c dry $\sim 300 \text{ kg}$; propellant $\sim 40 \text{ kg}$; total launch $\sim 500 \text{ kg}$. • Dimensions at launch: diameter $\sim 2.5 \text{ m}$; height: $\sim 3.5 \text{ m}$ <i>including both Cassegrain antennae</i>. • Attitude control: spin-stabilized spacecraft. • Navigation: Doppler, range, and possibly VLBI and/or ΔDOR. • Pointing: control $6 \mu\text{rad}$; knowledge $3 \mu\text{rad}$; stability $0.1 \mu\text{rad/sec}$. • Telemetry: rate 1 Kbps.
Lifetime	<p>7 years (nominal for velocity of 5 AU/year); 12 years (extended). 5 years (nominal for velocity of 10 AU/year); 8 years (extended).</p>

The determination of the anomaly will be of great scientific interest and value. Even if, in the end, the anomaly is due to some systematic, this knowledge will greatly aid future mission design and navigational programs. But if the anomaly is due to some not-understood physics, the importance would be spell-binding. The benefits to the community from this program would then be enormous.

But addressing this specific problem has motivated thought on a more general one. Our knowledge of the dynamical metrology of the outer solar system is relatively very poor. The Pioneers yielded the best measurements we have for deep-space hyperbolic orbits. These measurements were imprecise compared to what we could hope for today.

Our mission will use already existing navigation methods to conduct the most precise spacecraft navigation ever performed in deep space. It will rely on a novel spacecraft design to minimize the effects of small forces acting on the craft from both external and internal causes. It will have a navigational accuracy two orders of magnitude better than that currently available. With its advanced spacecraft design and operations, the mission will reduce systematics to an unprecedented level. This will help develop the critical expertise that will be needed to create the low-noise environments needed for precision space deployments of the 21st century. Thereby it will allow special tests of fundamental physics in space. All required technologies have already been demonstrated. This mission has no analogs: it is a unique natural extension of precise gravitational experiments in the solar system.

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